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Three-dimensional hydrofacies assemblages in ice-contact/proximal sediments forming a heterogeneous 'hybrid' hydrostratigraphic unit in central Illinois, USA

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Abstract Three-dimensional (3-D) hydrostratigraphic modelling of glacial sediment assemblages was undertaken as part of a groundwater study in central Illinois, USA. Sediments comprising these assemblages, informally referred to as the Glasford deglacial unit, form discontinuous sand-gravel layers including small aquifer zones, and fine-grained interstratified layers that may impede groundwater movement. This unit is stratigraphically above a regional aquitard overlying the important Mahomet aquifer. The study improves understanding of the internal stratigraphic architecture and hydrostratigraphic character of the unit. Data include descriptions of continuous cores, profiles of near-surface and downhole geophysical logs, and sediment descriptions from water well logs. Discrete bounding surfaces constructed using gOcad represent the main lithofacies assemblages forming a 3-D framework. The framework was further partitioned into a 3-D cellular grid for mapping the spatial distribution of fine- and coarse-grained facies. Hydraulic conductivity (K_G) estimates were used to convert these lithofacies into hydrofacies. Medium- to coarse-grained hydrofacies (K_G=1.25×10^{-5} m/s) represent 46 % of the total volume, the remainder being fine-grained hydrofacies (K_G=3.01×10^{-8} m/s). The spatial pattern of these hydrofacies is highly heterogeneous, thus, designating the Glasford deglacial unit as an aquifer or aquitard would be conceptually misleading. The term "hybrid hydrostratigraphic unit" is introduced to better represent conceptually this type of unit in hydrostratigraphic models.

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Introduction

In the glaciated regions of North America, studies of glacial sediment assemblages have led to significant understanding of water resources such as those hosted in large moraine systems (e.g., Gerber and Howard 2002; Martin and Frind 1998) or aquifers in buried valleys (e.g., Cummings et al. 2012; Herzog et al. 2003; Hackley et al. 2010; Kehew and Boettger 1986; Ritzi et al. 2000; Shaver and Pusc 1992; van der Kamp and Maathuis 2011; Wilson et al. 1998). One such buried-valley aquifer is the Mahomet aquifer in central Illinois, USA, which supplies groundwater to nearly one million people (Regional Water Supply Planning Committee 2009). Central Illinois is an area where an extensive knowledge base has been compiled about the character and distribution of the near-surface Quaternary-aged sediments (Johnson et al. 1997; Mickelson and Colgan 2003; Richmond and Fullerton 1986).

For a regional groundwater study of the Mahomet aquifer over the Mahomet Bedrock Valley (MBV; Fig. 1), a 3-D geological model and a groundwater flow model were created (Roadcap et al. 2011; Stumpf and Atkinson 2014; Stumpf and Dey 2012). The geological model was constructed by the Illinois State Geological Survey to represent the spatial distribution of formal and informal lithostratigraphic units, which are important in the regional stratigraphy. The lithostratigraphic units depicted in the model are laterally extensive and many represent important aquifers and aquitards lying over the MBV between the land surface and top of bedrock. These include not only the Mahomet aquifer at the base of the valley, but also several overlying units.

The geological model contains the major, laterally extensive lithostratigraphic units (Fig. 2) that were ultimately assigned to hydrostratigraphic units by the authors (Fig. 3) due to their contrasting textural character and provides a

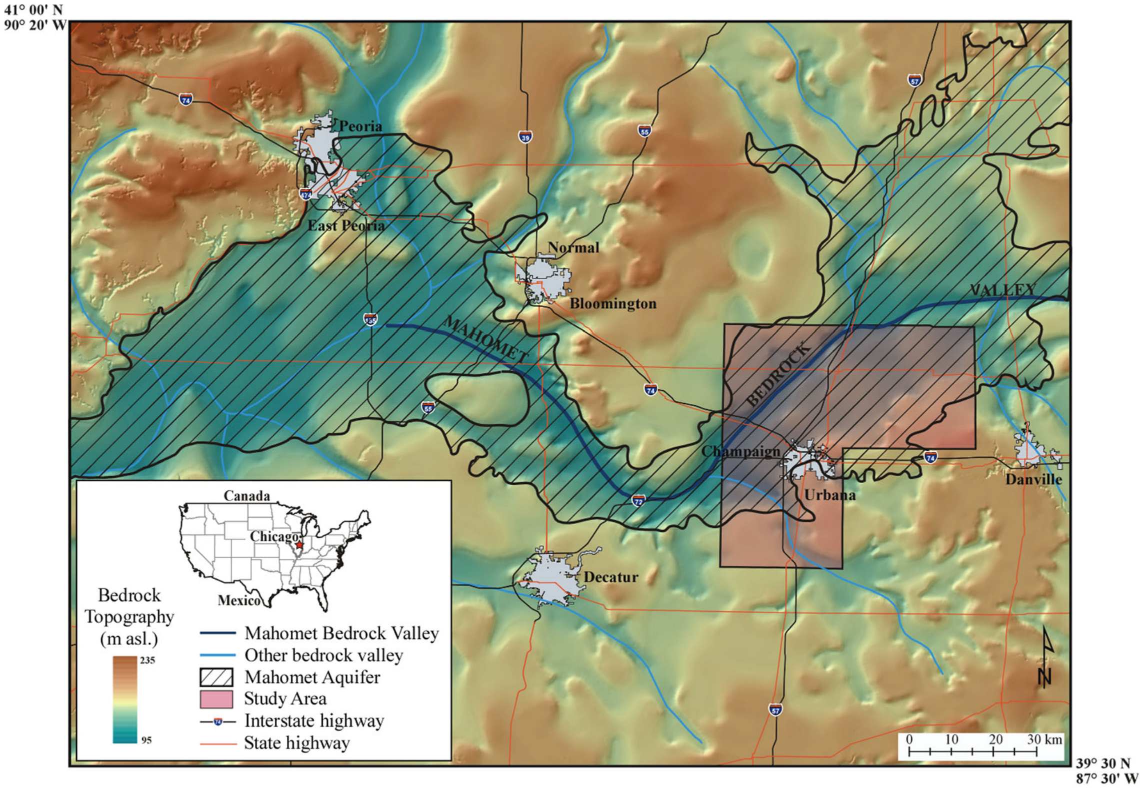

Fig. 1 Location of the modelling study in central Illinois. The boundary of the study area is overlain on the coloured hillshaded topography of the bedrock surface compiled by Herzog et al. (1994). The location of bedrock valleys are from Horberg (1950). The boundary of the Mahomet aquifer follows the boundary of major sand and gravel aquifers in central Illinois (Illinois State Geological Survey 1996). Source: Geology of the Mahomet Aquifer in Champaign County (http://isgs.illinois.edu/geology-mahomet-aquifer-champaign-county). ©2013 University of Illinois Board of Trustees. All rights reserved. Figure courtesy of the Illinois State Geological Survey

framework for including geological information from the subsurface into a groundwater flow model. However, this geological model only contains information describing the geometry of laterally extensive lithostratigraphic units through

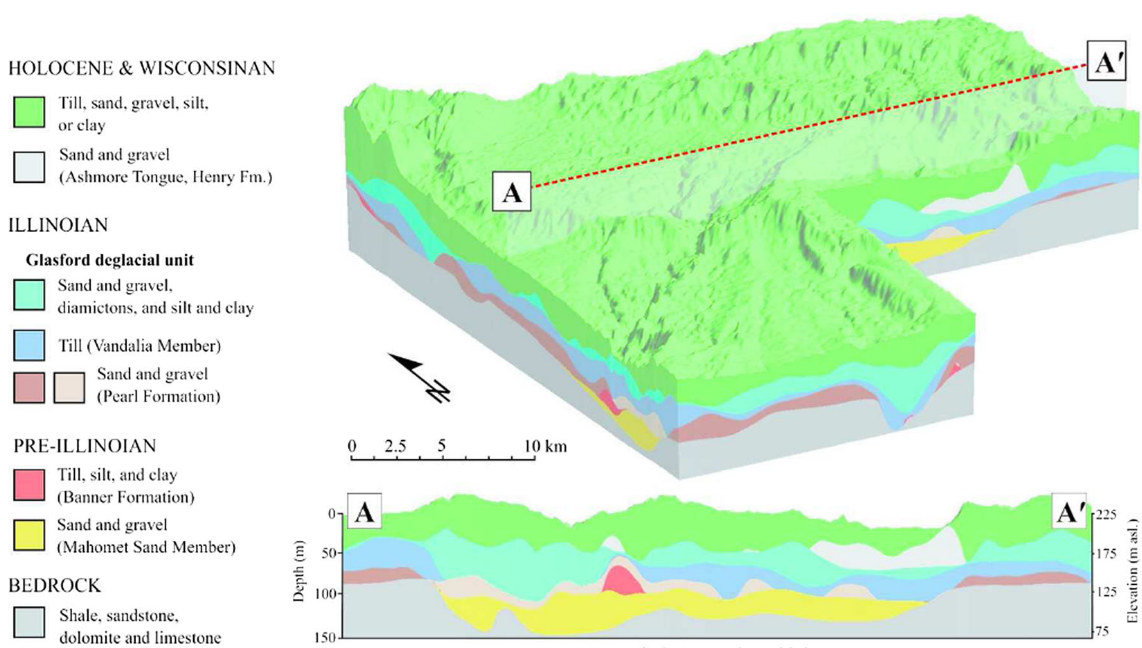

Fig. 2 A regional scale geological model developed for the study area. Cross section *A–A′* displays the geologic mapping units differentiated in the model

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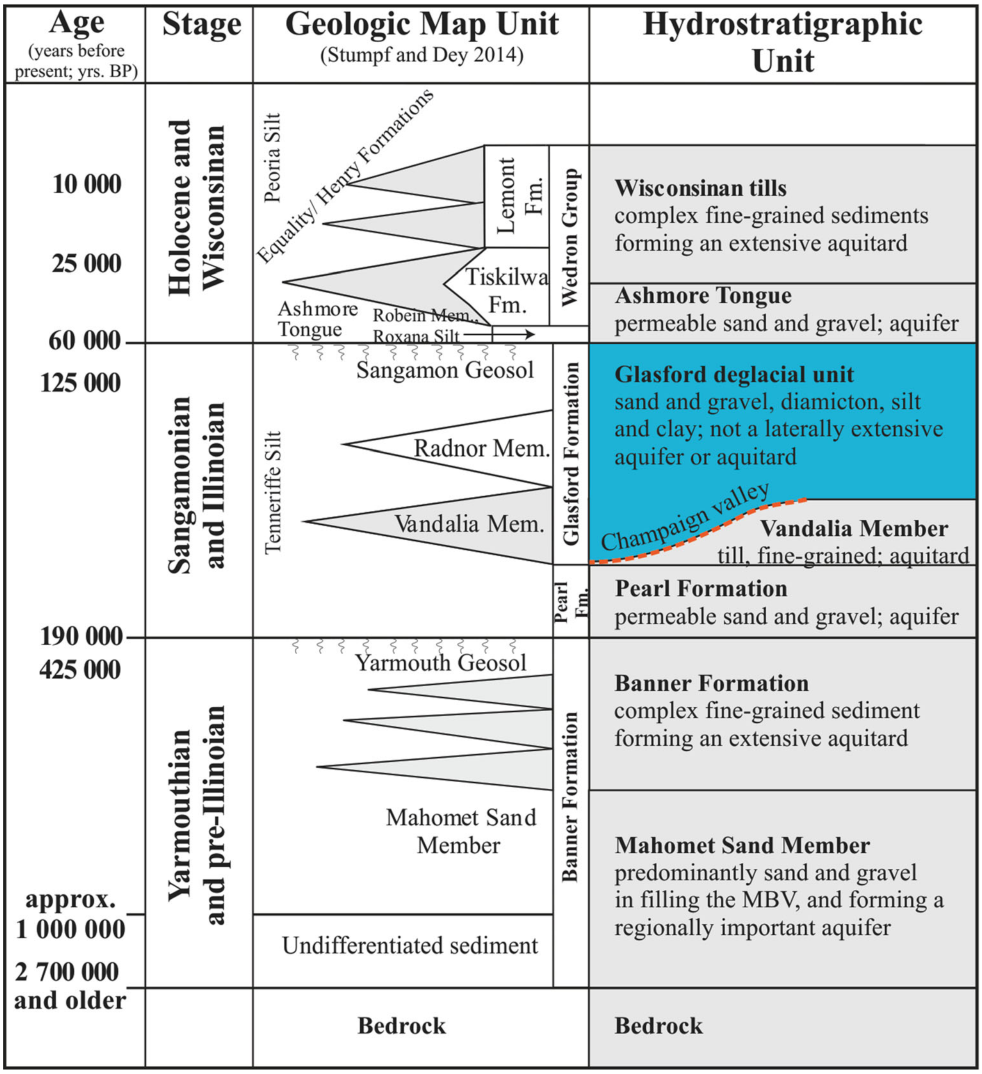

Fig. 3 Hydrostratigraphic units of the study area, partially based on the lithostratigraphy of Quaternary-age sediments in central Illinois from Hansel and McKay (2010). Information pertaining to each unit's lithology, distribution, and hydrogeological character are provided. Source: Stumpf and Dey (2012). ©2012 University of Illinois Board of Trustees. All rights reserved. Figure courtesy of the Illinois State Geological Survey

broad bounding surfaces. This model does not contain the structure for storing information describing the internal heterogeneities of each unit required to conduct more detailed hydrogeologic studies.

During the regional groundwater study, one specific unit, informally named "Glasford deglacial unit", became the focus of further study (Atkinson 2011; Atkinson et al. 2011) after realizing the potential for hydraulic connections through the unit, which may have a major impact on water quantity and quality in the underlying Mahomet aquifer and the discontinuous overlying aquifers. More specifically, the Glasford deglacial unit was designated an aquitard unit in the regional-scale model (Fig. 2; Stumpf and Dey 2012), but this was considered a major simplification as it has been known that the unit includes numerous discontinuous layers of sand and gravel. Some of these coarse layers are extensive enough to represent small aquifer zones that yield enough groundwater to residential wells (Larson et al. 2003a). Partitioning the Glasford deglacial unit into internally consistent facies assemblages is an initial step into incorporating a higher degree of heterogeneity within the geological model. These assemblages could be characterized in terms of hydraulic conductivity (hydrofacies) in an effort to advance understanding of hydrostratigraphy in central Illinois with the ultimate goal of improving understanding of groundwater systems in the region.

This paper presents the methods and procedures used in modelling the major (kilometer-scale) facies assemblages within the informal Glasford deglacial unit, their geometry and sedimentological character, as well as their general hydraulic conductivity, which gives insights into their hydrofacies characteristics. This case study also highlights some of the challenges in characterizing a broad subsurface unit with a well-defined top and bottom, but that includes numerous coarse-grained bodies, which locally form small aquifer zones separated by finer-grained confining layers.

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Study area, geology, and hydrogeology

This paper focuses on an approximately 3,000 km^2 area covering 30 townships in central Illinois located approximately 200 km south of the city of Chicago (Fig. 1). In the study area, the MBV is a prominent feature of the bedrock surface (Fig. 1), forming the western part of the Mahomet-Teays Bedrock Valley System (Horberg 1945) that extends from West Virginia to central Illinois. In Illinois, the bedrock valley system was formed during pre-glacial times (late Tertiary or early Quaternary periods) as rivers incised into Pennsylvanian-age shale, Mississippian-aged limestone and dolomite, and Silurian- to Devonian-aged limestone and dolomite (Kempton et al. 1991; Stumpf and Dey 2012). These sedimentary rocks generally dip towards the south into the Illinois Basin, but the regional dip is cross-cut locally by the LaSalle Anticlinorium, a structural belt that trends from north to south across the eastern part of the study area (Nelson 1995).

In this part of Illinois, the bedrock surface is buried beneath successive units of Quaternary-aged sediments that form the generally flat-lying surface topography. Intervening landforms provide gentle rises in relief; however, a more rugged paleotopography is buried beneath these sediments. Within the study area, Quaternary sediments are typically less than 80 m thick, but can reach thicknesses of 130 m over the MBV (Kempton et al. 1991). Considerable effort and resources have been directed to understand the extent and internal composition of the deposits filling the MBV and making-up the Mahomet aquifer (Herzog et al. 1995; Kempton et al. 1991; Soller et al. 1999; Stumpf and Dey 2012). Detailed subsurface investigations (i.e., drilling and surface and downhole geophysical surveys) have been undertaken to characterize the Mahomet aquifer, which provides extensive groundwater supplies to central Illinois. This important aquifer consists of sediments deposited during the Illinoian and Pre-Illinoian stages (Horberg 1945; Larson et al. 2003b; Wilson et al. 1998; Fig. 3). They are predominantly composed of sand and gravel of glaciofluvial or fluvial origin, but locally consist of deposits of till and glaciolacustrine silt and clay formed during earlier glacial advances, which are preserved and interstratified with the coarse-grained sediments. Despite the presence of finer-grained layers, the Mahomet Sand Member (Fig. 3) is best described as an aquifer, the Mahomet aquifer, as it contains several productive zones and the confining beds do not greatly affect the hydraulic continuity of the system (e.g., Stumpf and Dey 2012).

Deposits formed during the Illinoian, including the Pearl Formation, the Vandalia Member till, and Glasford deglacial unit, overlie the Mahomet aquifer in the study area, and are rarely exposed at the land surface (Figs. 2 and 3). The Glasford deglacial unit contains discontinuous deposits of sand and gravel forming unnamed aquifer zones supplying small amounts of groundwater for domestic uses. These groundwater supplies have been shown to be affected, locally by increased water usage, climate change, and extraction of groundwater from deeper, higher capacity wells (Larson et al. 2003b; Roadcap et al. 2011).

Geology of the Glasford deglacial unit

The Glasford deglacial unit is an informal lithostratigraphic unit named by Atkinson et al. (2011) to represent a sequence of Illinoian-age deposits in central Illinois. This unit includes deposits of sand and gravel, diamicton, and silt and clay that lie above diamicton (till) assigned to the Vandalia Member till deposited during the Illinoian Stage (Fig. 3), and lie below sediments assigned to the Ashmore Tongue of the Henry Formation and Tiskilwa Formation deposited during the Wisconsinan Stage (Fig. 3). The Glasford deglacial unit is therefore bounded by laterally extensive and well-defined lithostratigraphic units. Internally, it has been divided into different architectural elements and facies assemblages (Atkinson 2011). Several processes (e.g., fluvial or debris-flow processes) have been proposed for their deposition (Atkinson 2011; Atkinson et al. 2011). These sediments have also been interpreted as subglacial till with interbeds of sand, gravel, and silt deposited by glaciers (e.g., Johnson et al. 1972; Willman and Frye 1970) or part of a subglacial/proglacial sedimentary sequence (Stumpf and Atkinson 2014).

Previous understanding of the till stratigraphy of Illinoian deposits included two tills, the Vandalia and Radnor members. The Vandalia Member till has been well studied in southern and central Illinois, and this stage of glaciation was marked by extensive stagnation during deglaciation (e.g., Grimley et al. 2011). Deglaciation resulted in sedimentation on the Illinoian drift plain including: sand, sand and gravel, silt and partially sorted diamictic material, which reflect ice-contact and/or proglacial deposits proximal to the ice margin (Hansel and McKay 2010; Johnson 1976), hereafter referred to as ice-marginal. However, more recent study of these deposits from continuous cores, downhole geophysical logs, and near-surface geophysical data (Stumpf and Dey 2012) question assigning this diamicton to the Radnor Member.

In part of central Illinois, a recent study of the subsurface deposits have identified a buried valley (Stumpf and Dey 2012), informally named the “Champaign valley” by Atkinson (2011) (Figs. 3 and 4). The sediments infilling this valley are inset into older tills and glaciofluvial sediments. The sediment infilling the Champaign valley is overlain by a tabular body (Fig. 4), which includes sediment interpreted to be deposited during the deglacial phase of the Illinoian glaciation (Stumpf and Dey 2012). Therefore, the Glasford deglacial unit includes two distinct subsurface architectural elements of possible regional extent: (1) the Champaign valley filled with sediment composing three deglacial sediment assemblages (V1–V3; Fig. 5; Table 1), which is inset into the regional Vandalia Member till; and (2) an overlying tabular body with three facies assemblages (A–C; Fig. 5 and Table 1). These architectural elements were first differentiated from geophysical profiles, drill cores and borehole data, and classified using architectural element analysis techniques developed by Gaud et al. (2004) and Miall (1977, 1985). Specifically, the Champaign valley is filled by interstratified, massive, and bedded sand (V1 and V3), as well as by bedded to massive silt and clay, and diamicton

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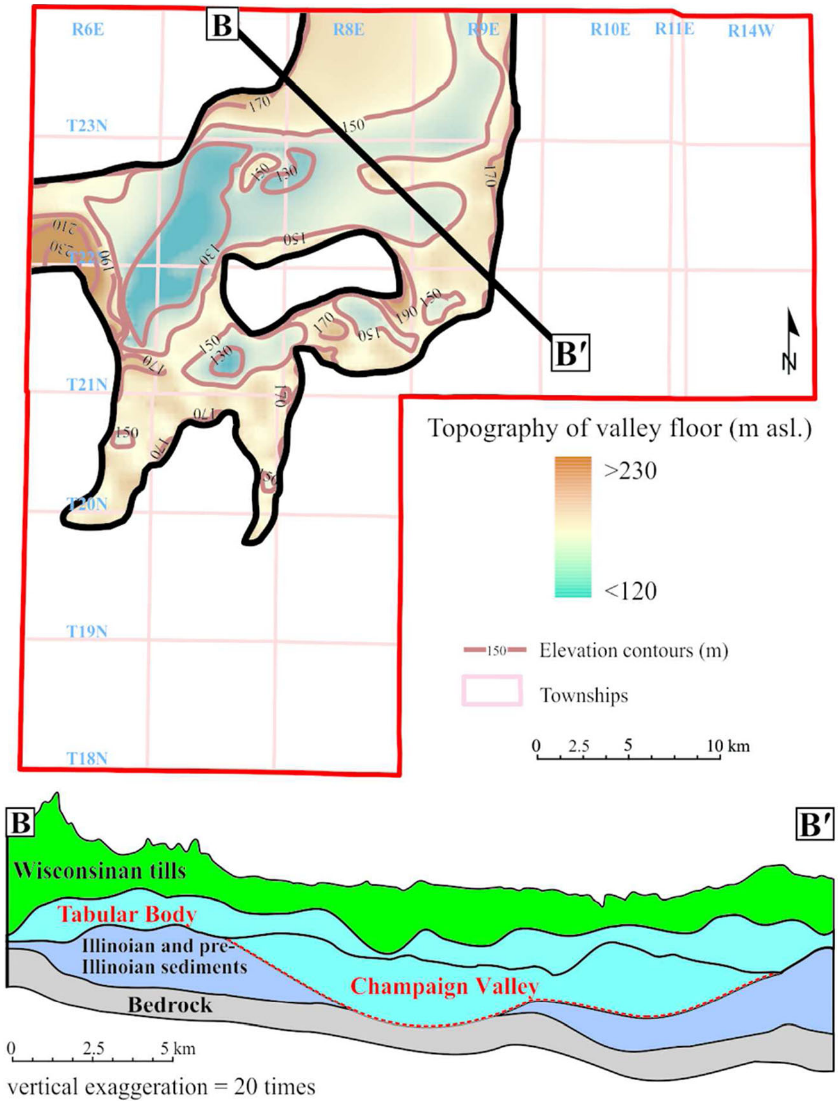

Fig. 4 Cross section *B–B′* over the Champaign valley presents a simplified hydrostratigraphy for the study area. Thick deposits of Wisconsinan-age sediment (mostly till) overlie the Glasford deglacial unit. The Glasford deglacial unit is composed of a tabular body and deposits filling the Champaign valley. The deposits filling the Champaign valley are inset into older sediments assigned to the Illinoian and Pre-Illinoian stages. In some areas, the bottom of this valley is on bedrock

(V2; Table 1). The tabular body above the valley-fill consists of a package of highly heterogeneous sediment, namely discontinuous interstratified sand (B), diamicton and other fine-grained facies (A and C; Table 1).

Hydrostratigraphy

As hydrostratigraphy is concerned with identification of the surface and subsurface units on the basis of their hydrogeologic properties (e.g., Maxey 1964; Seaber 1982), the subsurface is generally partitioned into unconfined or confined permeable aquifer layers and aquitard layers that impede groundwater movement. Aquifers and aquitards are often referred to as hydrostratigraphic units, although there is a paucity of work formally defining what is a "hydrostratigraphic unit" (Seaber 1988). Because these units have been defined in a variety of ways in the literature, it is important to briefly explain how the different terms are used herein. In this study, a hydrostratigraphic unit is defined as a laterally continuous (kilometer-scale) layer of sediments whose range and spatial distribution of hydraulic conductivity contrasts with that of adjacent layers. A hydrostratigraphic unit can therefore be an aquifer, an aquitard, or a distinct layer within an aquifer or aquitard. For example, depositional elements (i.e., channel fill or a deltaic sequence) of an aquifer may be distinguished from adjacent elements within the same aquifer unit on the basis of their sedimentological characteristics and derived hydraulic conductivities (Heinz and Aigner 2003; Klingbeil et al. 1999). A hydrostratigraphic unit can also correspond to a lithostratigraphic unit of any rank if both units share the same bounding surfaces. Hydrostratigraphic units may be further partitioned into individual hydrofacies

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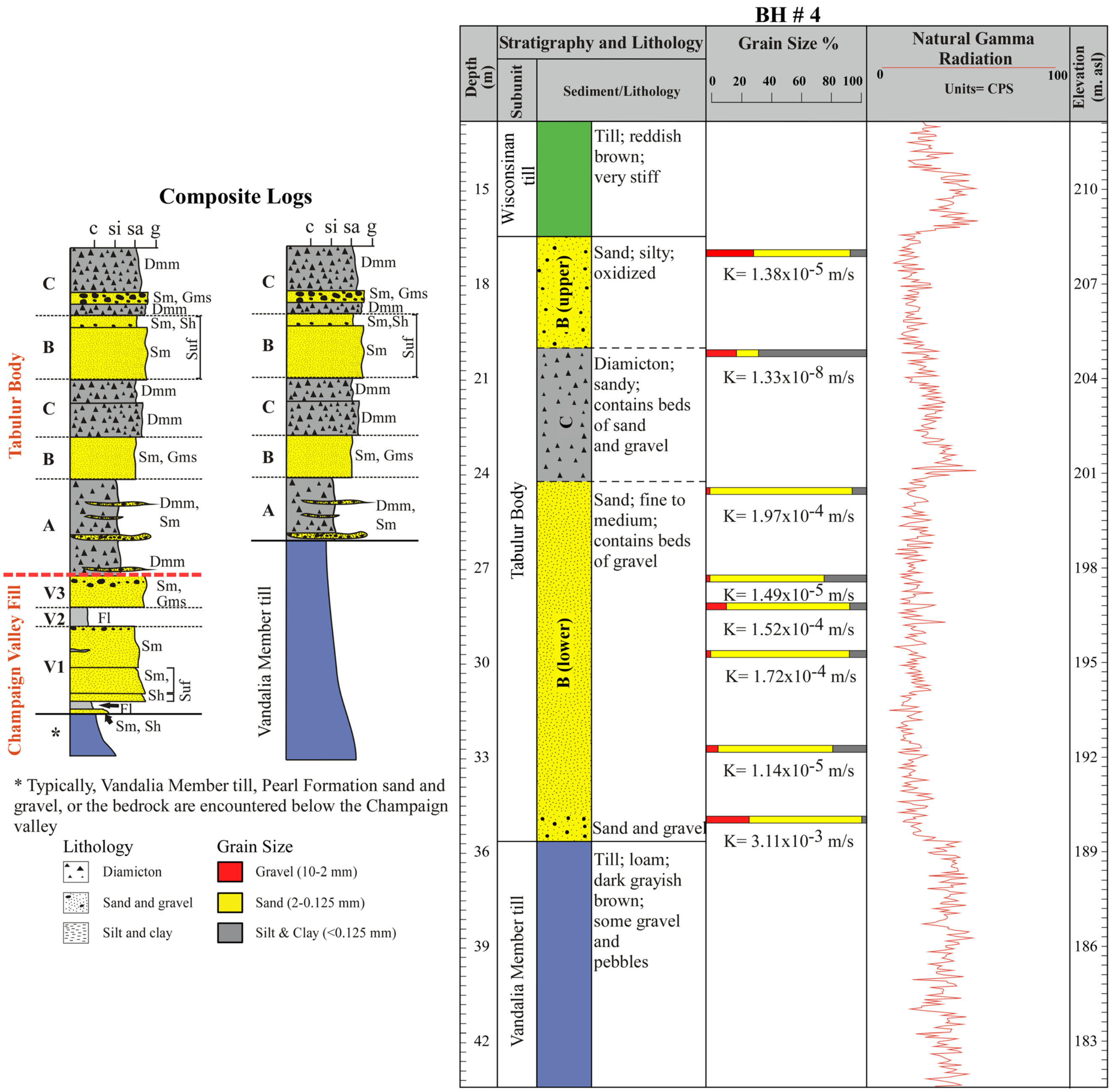

Fig. 5 The Glasford deglacial unit is further subdivided into separate hydrofacies assemblages. In the composite log, the hydrofacies assemblages *V1*, *V2*, and *V3* are found in the Champaign valley, and assemblages *A*, *B*, and *C* are assigned to the tabular body of the Glasford deglacial unit. The geologic and natural gamma logs from *BH-4* shows the tabular body and the transition to the Vandalia Member till. The hydrostratigraphic units, hydrofacies assemblages, grain size, and calculated hydraulic conductivity (*K*) are also shown for BH-4. The lithofacies coding system used is from Eyles et al. (1983) and Miall (1977). The natural gamma radiation was recorded in counts per second (*CPS*)

(e.g., Fig. 6). Hydrofacies are generally recognized on the basis of sediment texture (grain size, sorting), fabric and packing (e.g. Kostic et al. 2005); a hydrofacies should be characterized by relatively homogenous hydraulic conductivity. Because many sedimentary successions are cyclic in nature, hydrofacies (A, B, C) can be stacked in a repetitive succession forming consistent assemblages (A-B-C), which may be more useful or practical for kilometer-scale mapping purposes.

The scale of a study area and the techniques used to characterize the subsurface largely determines the degree of heterogeneity that can be incorporated in a hydrostratigraphic model (Heinz and Aigner 2003). Model scales are variable and depend on the objectives of the project (e.g., regional 10–100 km or local 1–10 km water supplies), and as a result, some models represent major hydrostratigraphic units as homogeneous with limited internal variability (e.g. Ross et al. 2005), whereas

 DOI 10.1007/s10040-014-1156-7

Table 1 Classification system for the hydrostratigraphy of the Glasford deglacial unit

	Facies assemblage	Sediment characteristics
Tabular body		
	C	Diamicton with few beds of sand and gravel and/or silt and clay. Closely related to assemblage A
	B	Coarse to fine-grained sand with beds of gravel and pebbles
	A	Discontinuous, highly compacted diamicton with sand and gravel interbeds
Champaign valley fill		
	V3	Fine to medium sand with some gravel
	V2	Silty loam diamicton and laminated and/or massive silt and clay
	V1	Thick succession of very fine to coarse sand, or gravelly sand

other models representing areas of smaller or local extent are developed to represent heterogeneities and highly variable sediment characteristics (e.g., hydrofacies scale; Weissmann and Fogg 1999).

Regional scale hydrostratigraphic model

In central Illinois, glacial sediments of the Quaternary Period found at land surface and in the subsurface have a complex, but mappable pattern of occurrence. As shown in Fig. 2, the regional geological model from land surface to bedrock of the study area (Stumpf and Dey 2012) incorporates the main lithostratigraphic units, although some units were combined. This model depicts the sediments deposited during each glaciation (i.e., Wisconsinan, Illinoian, and Pre-Illinoian) including diamicton (mostly till) with large variations in grain size range, sand and gravel (glaciofluvial sediment), and/or sand, silt, and clay (glaciolacustrine sediment). The grouping of some of the units was based upon lateral extent, overall textural characteristics (e.g., grain size distribution), and stratigraphic position (Stumpf and Dey 2012). Due to the emphasis on sediment texture, the units in the geological model can be compared directly to hydrostratigraphic units introduced in this study representing a total of eight important and extensive aquifers and aquitards in the region (Fig. 3). There are, however, exceptions to the subdivision based on texture and the Glasford deglacial unit is one of them. Although at a regional scale it was considered an aquitard (Stumpf and Dey 2012), it contains several small aquifer zones. Prior to this study, the stratigraphic architecture of the unit had not been studied and was poorly understood; therefore, further analysis and subsurface mapping was required (this study).

Material and methods

Data compilation, analysis, and standardization

The modelling of the Glasford deglacial unit involved compilation of existing data, development of a project database, standardization of data, and assessment of the quality of the data for modelling purposes. These are typical initial steps in most regional scale geomodelling projects (e.g., Allen et al. 2008; Artimo et al. 2008; Kostic et al. 2005; Lelliott et al. 2006; Ross et al. 2005). Subsurface geological and geophysical information including descriptions of continuous cores and washed samples from drilling operations, geologic logs from water wells, engineering tests, and coal, oil and gas exploration, and geophysical profiles and logs were the primary sources of information used for modelling the Glasford deglacial unit. There were limited field outcrops in the study area that exposed the Glasford deglacial unit. Descriptions of 38 continuously cored boreholes with downhole geophysical logs (ranked 5 in Table 2), 70

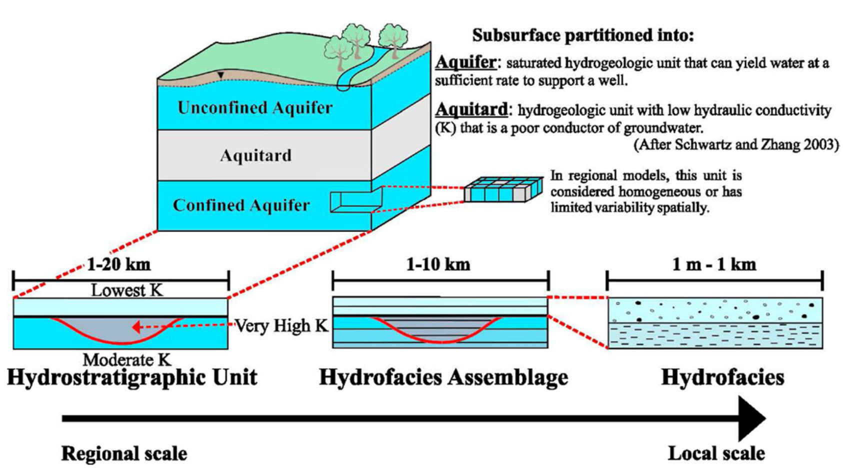

Fig. 6 The concept of hydrostratigraphic units, and its application at regional to local scales. Typically, the development of conceptual models involves subdividing hydrostratigraphic units into aquifers or aquitards. For the modelling of the Glasford deglacial unit, the hydrostratigraphic unit (at the aquifer level) was subdivided into hydrofacies assemblages that comprise two distinct architectural elements, sediments that fill the Champaign valley and a tabular body (Figs. 4 and 5)

 DOI 10.1007/s10040-014-1156-7

Table 2 Criteria for evaluating data quality and location accuracy in constructing the geological model of the Glasford deglacial unit. The procedure used is modified from Ross et al. (2005)

Rank	Data quality	Type of data/location accuracy	Type of data collection
5	Very high (used)	Descriptions of continuous sediment core or washed sediment samples with downhole geophysical logs from the same borehole. The borehole was located using a GPS, field descriptions, or tax-parcel data used to verify land owner information	Core or washed samples collected and described by a geologist
4	High (used)	Description of washed samples or downhole geophysical log from the same borehole. The borehole was located using a GPS, field descriptions, or tax-parcel data used to verify land owner information	Washed samples collected and described by a geologist
3	Moderate (used)	Washed samples (incomplete) and complete description of the geology from the same borehole, or washed samples or downhole geophysical log with incomplete description of the geology from the same borehole. The borehole was located using a GPS, field descriptions, or tax-parcel data used to verify land owner information	Washed samples described by a geologist
2	Fair (manually selected)	Geologic logs from boreholes chosen for the modelling that contain information consistent with the geology from nearby boreholes (ranked from 5 to 3 in quality). The borehole was located with information submitted by the driller	Geologic log submitted by the driller. A geologist was not involved
1	Problematic (not used)	Geologic logs not used in the modelling. There is an incomplete record or log that contains information that does not correlate with the geology in nearby boreholes. The location of the borehole may not be verified	Geologic log submitted by the driller. A geologist was not involved
0	Incomplete (not used)	Incomplete record. Unable to verify the location of the borehole	If the geologic log is available, the log was submitted by the driller. A geologist was not involved

downhole geophysical logs from other boreholes (ranked 5 to 3 in Table 2), and 799 geologic logs from boreholes drilled for installing water wells were data used to construct the model (Fig. 7).

A manual process was applied to select the most complete records that best represent the geology of an area where multiple records are available and to reject records that are incomplete or lack sufficient detail about the sediments comprising the unit. Another typical, yet important aspect of the data is that boreholes are clustered in some parts of the study area. The final selection of borehole logs with a fair quality rating included a manual declustering in areas of sufficient high quality data and/or to ensure one borehole log per section (Fig. 7) was selected where available, and when appropriate, was consistent with nearby reliable data. As a result of these 'filtering steps', only records from 907, out of the 1,662 boreholes available, were used as necessary data constraints to build the model. Each dataset was merged into a relational database for further analyses. Standardizing the data allowed the numerous descriptions to be grouped into 30 sediment classes (e.g., diamicton, gravelly silt, pebbly clay). This classification was further simplified to 20 lithofacies classes—e.g., D represents massive matrix-supported diamicton (Dmm) in Fig. 8a—following the procedure used by Ross et al. (2005). Although each dataset was standardized to provide a common coded attribute for all lithofacies, the quality of data in each record was quite variable. Therefore, all data were ranked according to criteria presented in Table 2. Data considered to be highest in quality (quality rank 5 to 3, Table 2) were key data for constructing the model of the Glasford deglacial unit.

The use of water wells and other boreholes not originally described by a geoscientist in regional geomodelling studies can lead to inconsistencies and special care must be taken before incorporation into the model set of constraints. This is a problem that has long been recognized by the geomodelling community involved in regional subsurface investigations and to which there is no simple solution. One "cautious" approach is to only consider data from water wells that have no apparent inconsistencies or obvious errors when compared with surrounding high-quality boreholes (e.g. Ross et al. 2005). In this study, these apparently consistent logs were ranked 2 for the overall quality (Table 2) and used to constrain surface interpolation between high-quality boreholes (i.e., data quality rank 5 to 3, Table 2) knowing they would not affect in any major way the geometry of the units between high-quality data. The possibility cannot be excluded, however, that some rank 1 data, i.e. data with apparent inconsistencies relative to nearby high-quality data, may occasionally capture "real" complexity, but it was considered reasonable to flag these data as potentially inconsistent until this complexity is verified with more reliable data. Rank 1 data were thus not used in modelling the Glasford deglacial unit. Overall, where lower-quality data (rank 2, Table 2) tend to dominate the set of constraints

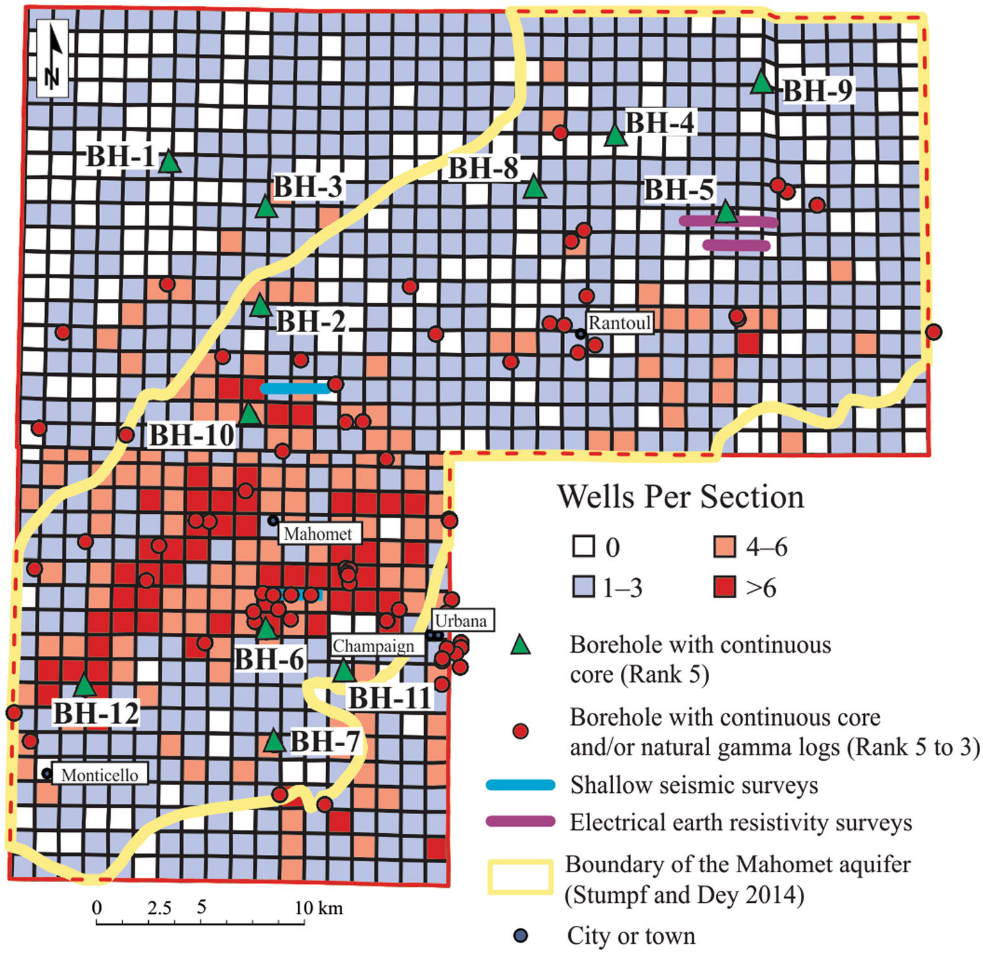

Fig. 7 Map showing the number of boreholes (per section) in the study area. The highest quality data collected for mapping the geology at a regional study (i.e., continuous cores and geophysical logs) are shown and were primarily from boreholes drilled over the MBV. High quality data include descriptions of continuous core, downhole geophysical logs and profiles from near-surface geophysical surveys. These data were used to constrain the bounding surfaces of the units in the regional geological model (shown in Fig. 2). Information from selected boreholes provided key stratigraphic control to estimate unit geometries and the vertical succession of hydrofacies assemblages in the Glasford deglacial unit

(cells far from high-quality data shown on Fig. 7), the geometry and internal character of the unit should have a higher uncertainty. These areas of the model should also be priority targets for future studies.

In addition to the borehole data, downhole geophysical logs, including natural gamma radiation, resistivity, neutron, spontaneous potential and single-point resistance were analyzed to infer a relative grain size or mineralogy for the sediments (Ismail et al. 2014). Geophysical logs were measured continuously in the entire borehole with measurements taken every 0.03–1.00 m. Where core recovery was incomplete, the downhole geophysical logs provide the most continuous record that can be used to infer sediment type or glacial sedimentary sequence (Bleuer 2004).

For the construction of the regional geological model, near-surface geophysical data were collected along linear transects (Stumpf and Dey 2012). Electrical earth resistivity (EER) profiles were collected along approximately 10 km of line roadway and seismic reflection data along 8.8 km of line (Fig. 7). For modelling the Glasford deglacial unit, the geophysical data were primarily used to identify the upper and lower contacts of the unit and to infer the relative grain size of sediments in the unit (Larson 1994; Stumpf and Ismail 2013).

Stratigraphic and lithofacies classification

Detailed geological information from boreholes, including material type, texture, colour, internal structures and bedding, and mineralogy, along with geophysical data and profiles as well as information from previously published geological frameworks (e.g., Kempton et al. 1991; Willman and Frye 1970) were used altogether to delineate the major architectural elements and their internal lithofacies assemblages.

The top of the Glasford deglacial unit was identified by marker beds, which included pinkish-brown to gray till (Tiskilwa Formation), organic-rich peat silt (Robein Member), or a paleosol (Sangamon Geosol; Fig. 3). The latter, was easily identified in the core samples since the sediment that the soil is developed in is commonly

 DOI 10.1007/s10040-014-1156-7

leached of primary carbonate minerals, oxidized, and contains an accumulation of elluvial clay typical of Bt soil horizons. Also, in the geologic logs from boreholes these sediments are described as black or green clay, oxidized sediment. The lower contact of the Glasford deglacial unit was easily delineated in boreholes with cores and downhole geophysical logs due to the sharp contact with the contrasting underlying deposits of the Illinoian and Pre-Illinoian glaciations (Fig. 5). In most of the boreholes, sediments of the Glasford deglacial unit overlie a gray loamy till that is highly consolidated. The till is assigned to the Vandalia Member of the Glasford Formation. Typically, there is a notable change in the counts per second (CPS) on the log of natural gamma radiation between the Glasford deglacial unit and till of the Vandalia Member (Fig. 5).

Geological modelling

A geological framework model (GFM) representing the stratigraphic architecture of the Glasford deglacial unit was developed using gOcad software. The top and bottom of the unit are taken from the regional geological model developed by Stumpf and Dey (2012), which are constrained by the same marker beds as described in the previous section. Using the information about the lithofacies classes (Fig. 8b) and the built-in discrete smooth interpolation (DSI) algorithm in gOcad software developed by Mallet (1989), triangulated surfaces were created representing the top of the mapped lithofacies assemblages (Fig. 8c). The DSI algorithm provides a global, best fit solution to define a geometric form using a series of interconnected nodes (Bonomi 2009), while honouring a set of user-defined constrains (e.g., maximum thickness) and a roughness criterion (Mallet 1989, 2002). A stratigraphic grid (SGRID) was generated from these triangulated surfaces (Fig. 8d) to represent the lithofacies assemblages as a volume in the model. Specific lithofacies assemblages, including coarse-grained deposits (i.e., sand, and sand and gravel) or fine-grained sediment (i.e., diamicton, silt, and clay) were assigned to each cell in the SGRID (Fig. 8d). Because the lithofacies were classified primarily on the basis of sediment texture and fabric/packing, they can be converted into hydrofacies using hydraulic conductivity estimates from grain size data.

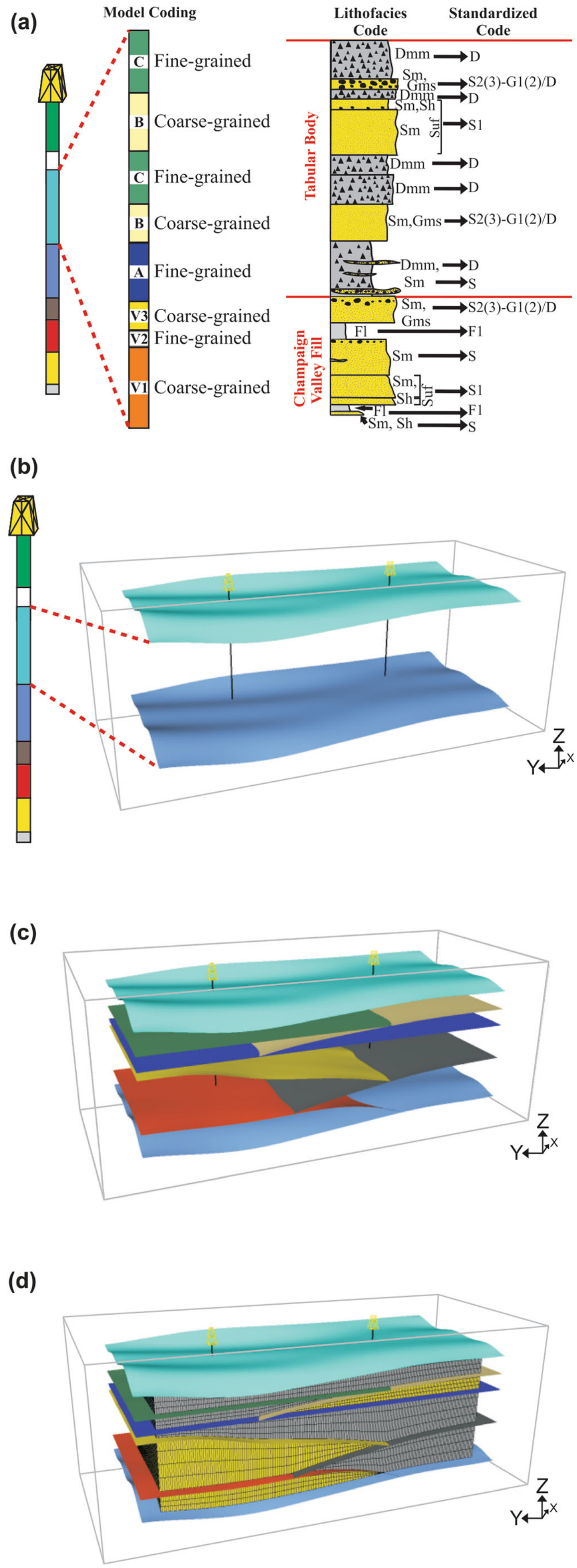

Fig. 8 The approach used to construct a geologic framework model (GFM) for mapping the geometries of hydrostratigraphic units. Initially, the data are imported into the geological model for gridding. Different grids can be developed from the same GFM (i.e., primary or secondary GFM) to differentiate hydrofacies assemblages from the idealized geology, for example from the Glasford deglacial unit (**a**). The primary GFM is shown containing the upper and lower bounding surfaces of the Glasford deglacial unit (**b**), while a secondary GFM is developed representing the hydrofacies assemblages (**c**). The GFM may be further modified to include curvilinear grids, to distinguish between the coarse- and fine-grained sediments in the unit, represented by the *yellow and gray shading*, respectively (**d**)

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Hydraulic conductivity

The geological model of the Glasford deglacial unit has been developed for use in regional hydrogeologic studies. To this end, it was designed to be populated with hydraulic conductivities for conversion of lithofacies to hydrofacies and for visual examination of potential hydraulic connectivity, pathways, or windows through the units. In this study, hydraulic conductivity values were determined using empirical formulae based on the grain size of bulk samples from sediments examined in selected continuous cores. The empirical formulae are often used for the determination of hydraulic conductivities from grain size distribution when in-situ aquifer testing data are not available (Freeze and Cherry 1979). Three empirical equations (Table 3) were chosen to model the hydraulic conductivity from grain size data of 55 samples representing the lithofacies assemblages. The complete grain size distributions can be found in Atkinson (2011). Final results were selected according to the grain size range of applicability of the formulas, which are detailed in Odong (2008), taking into account the textural characteristics of the sample.

Results

Composition, thickness, extent, and distribution of the Glasford deglacial unit

From the data analyses, standardization, and declustering discussed previously, only 54.5 % of the total data available were used to construct the model for the Glasford deglacial unit (Table 4). As shown, data in the very high, high, and moderate classes represent 11.91 % of the boreholes. Also, the upper and lower surfaces of the unit are better constrained over the MBV (Fig. 7). However, outside of the MBV, the model of this unit is constructed using a higher proportion of the lower quality data. A total of nine triangulated surfaces were created for this unit representing the top of the mapped facies assemblages, six of which are shown in Fig. 8c.

The thickness of sediments assigned to the Glasford deglacial unit is shown in Fig. 9. The unit is thickest over the Champaign valley, reaching a maximum of approximately 70 m. The Champaign valley is defined by an erosion surface on the top of the Vandalia Member till, which was recognized through geophysics and core analysis. As mentioned in the Geology of the Glasford Deglacial Unit section, the valley is filled with three deglacial sediment assemblages (V1–V3; Fig. 5; Table 1). Outside of this valley, the unit has a maximum thickness of approximately 45 m. These sediments are part of a large tabular body, which was also recognized through seismic profiles and borehole logs. The tabular body consists of interstratified sand (assemblage B) and diamicton with discontinuous layers of coarse and fine-grained sediment (assemblages A and C; Fig. 5; Table 1). The sediments comprising assemblages A, B, and C are discontinuous across the study area, which accounts for the variable thickness of the tabular body (Fig. 9 and Table 5).

Individual facies assemblages have also been measured in terms of thickness and volume of the Glasford deglacial unit. Thickness and volume of facies assemblages of the tabular body and Champaign valley are shown in Table 5. Deposits of sand and gravel composing each of the assemblages B, V1, and V3 have a mean thickness of

Table 3 Empirical equations for calculating hydraulic conductivity (K) from grain size distributions (after Odong 2008)

Empirical Equation	Formulae	Parameters	Applicability
Equation 1: Kozeny-Carman[a,b,c,d,e]	$K=\frac{g}{\nu}\times 8.3\times 10^{-3}\left[\frac{n^3}{(1-n)^2}\right]d_{10}^2$	Most widely accepted (not appropriate for either sediment with effective grain size >3 mm or clayey sediment)	Most useful for sediment having variable grain size distributions
Equation 2: Breyer[a,b,e,f]	$K=\frac{g}{\nu}\times 6\times 10^{-4}\log\frac{500}{U}d_{10}^2$	Does not consider porosity of sediment. Most useful for sediment with heterogeneous grain size distributions or poorly sorted sediment. Appropriate if uniformity coefficient (U) is between 1 and 20, and the effective grain size is from 0.06 to 0.6 mm	Adequate for characterizing poorly-sorted sediment. Inappropriate for well-sorted sediment
Equation 3: Alyamani and Sen[a,e,f]	$K=1300[I_o+0.025(d_{50}-d_{10})]^2$	Used for poorly-sorted sediment. Uses intercept I_o taken directly from grain size distribution	Suitable for characterizing heterogeneous, poorly-sorted sediment

Where:

[a] K=hydraulic conductivity

[b] g=gravity (9.8 m/s^2)

[c] ν=kinematic viscosity

[d] $f(n)$=porosity function

[e] d_{10} or d_e=effective grain size diameter

[f] U=coefficient of grain uniformity (d_{60}/d_{10})

[g] I_o=intercept in mm of the line formed between the d_{50} and the d_{10} of the grain size distribution and associated statistics

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Table 4 Analysis of data quality

Rank	Classes of data quality	Number of records	Percent of total dataset	Percent per data quality class
5	Very high	65	3.91	7.17
4	High	35	2.11	3.86
3	Moderate	8	0.48	0.88
2	Fair (manually selected)	799	48.07	88.09
1	Problematic (not used)	711	42.78	0.00
0	Incomplete (not used)	44	2.65	0.00
	Total number of records used	907	54.50	
	Total number of records available	1,662	100.00	

3.76 m, and a maximum thickness of 9.41 m (assemblage B). Discontinuous deposits of diamicton and silt and clay composing each of the facies assemblages A, C, and V2 have a mean thickness of 2.81 m, and a maximum thickness of 8.99 m (assemblage C). However, in many areas deposits of silt and clay are relatively thin and rarely exceed 3 m in thickness.

The total volume of sediment in the Glasford deglacial unit is estimated to be 5.70×10^9 m^3, which represents about 3 % of the total sediment volume of the regional geological model (Fig. 2). The total volume of coarse-grained sediment (potentially aquifer materials) in the Glasford deglacial unit is approximately 54 % (Table 6). The remaining 46 % of the unit is composed of fine-grained sediment that is potentially aquitard material. The largest volume of coarse-grained sediment is found in the Champaign valley where facies assemblages V1 and V3 are delineated and where repeated layers of facies assemblage B are present in vertical sequence. As a result, by considering only the sediments within the Champaign valley, as much as 95.6 % falls within the coarse-grained facies (Table 6). In contrast, the tabular body overlying the valley contains 46.1 % coarse-grained sediment.

Hydraulic conductivities and hydrofacies of the Glasford deglacial unit

Hydraulic conductivities of the Glasford deglacial unit derived from empirical calculations made from grain size distributions of sediment samples for each hydrofacies assemblage are summarized in Table 7. Samples were taken from the continuous cores in seven boreholes to

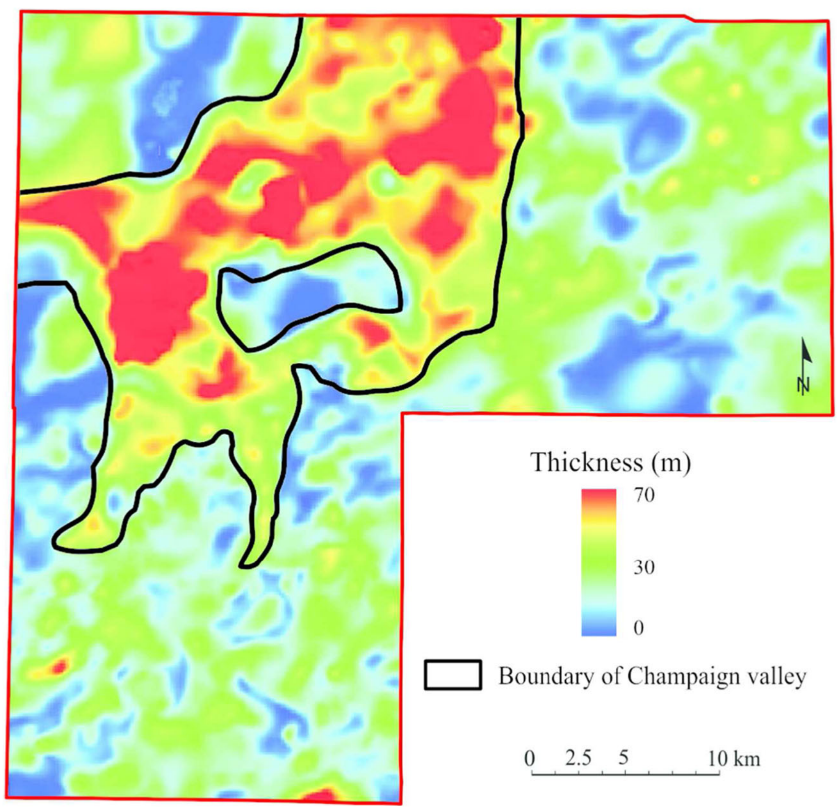

Fig. 9 Isopach map of sediment thickness for the Glasford deglacial unit in the study area. Over the Champaign valley, the unit includes both the tabular body and valley fill

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Table 5 Estimate of thickness and volume of the facies assemblages for the Glasford deglacial unit. All the volumes were calculated using built-in tools in the gOcad software. *SD* standard deviation

Facies assemblage	Thickness (m)				Volume (m^3)
	Median	Max	Mean	SD	
Tabular body					
C (upper): fine-grained	1.60	8.26	1.85	1.33	3.93×10^8
B (upper): coarse-grained[b]	1.86	9.41	2.00	1.46	9.25×10^8
C (lower): fine-grained	1.96	8.99	2.21	1.48	1.28×10^9
B (lower): coarse-grained	2.40	9.00	2.59	1.45	1.29×10^9
A: fine-grained	2.37	8.67	2.62	1.76	9.22×10^8
Champaign valley fill					
V3: coarse-grained	5.01	8.22	5.04	0.93	6.04×10^7
V2: fine-grained	4.43	8.62	4.56	1.24	3.88×10^7
V1: coarse-grained	5.35	8.99	5.42	1.10	7.91×10^8

[a] The facies assemblage B contains the largest volume modelled

represent each assemblage (Fig. 7). The hydraulic conductivities for the assemblages vary over a wide range between 10^{-4} and 10^{-9} m/s. The geometric average hydraulic conductivity (K_G), calculated given the wide range of values, is 4.93×10^{-6} m/s (Table 7). The difference in the calculated hydraulic conductivities can be correlated to changes in sediment type in this unit. Limited extrapolation of the data can be done as hydraulic conductivity is strongly influenced by the degree of lithological heterogeneity (Stephenson et al. 1988). However, very limited hydraulic conductivity data were previously available for the sediments assigned to the Glasford deglacial unit (e.g., Berg et al. 1984). Therefore, these analyses are a first step for converting lithofacies of the Glasford deglacial unit into hydrofacies based on hydraulic conductivity.

The K_G calculated for the coarse-grained material in the Glasford deglacial unit is 1.25×10^{-5} m/s (assemblages B, V3, and V1; Table 7). The highest hydraulic conductivities were calculated for sediment assigned to facies assemblage V1 taken from borehole BH-3 and facies assemblage B from borehole BH-6—Fig. 10; see also electronic supplementary material (ESM). These assemblages are therefore considered to represent distinct hydrofacies. The calculated hydraulic conductivities for individual samples are 5.86×10^{-4} m/s (BH-3) for hydrofacies assemblage V1 and 5.03×10^{-3} m/s (BH-6) for hydrofacies assemblage B (see ESM). Considering all results, the most voluminous sand and gravel hydrofacies assemblage, hydrofacies assemblage B, has a K_G of 4.50×10^{-5} m/s (Tables 5 and 7). Thinner deposits of sand and gravel within the Champaign valley fill (specifically V1 and V3) have a K_G of 5.85×10^{-6} m/s (V1) and 7.35×10^{-6} m/s (V3). The distribution of sediments with higher hydraulic conductivities varies vertically throughout the Champaign valley and tabular body. At the base of both the Champaign valley and tabular body hydraulic conductivity values tend to be higher, and decrease with increasing elevation in the architectural elements. The lowest hydraulic conductivity, 9.26×10^{-9} m/s, was calculated for hydrofacies assemblage C in an individual sample taken from borehole BH-6 (ESM; Fig. 10). Overall, the finer-grained sediments (assemblages V2, A, and C) composing the Champaign valley fill and tabular body have a K_G of 3.01×10^{-8} m/s. Although the finer-grained facies assemblages V2, A and C have similar hydraulic properties (Table 7) these units are also considered distinct hydrofacies as they are found in different architectural elements (i.e., V2 in the Champaign valley; A and C in the tabular body) and are separated stratigraphically.

Table 6 Volume and percentage of coarse- and fine-grained sediments in the Glasford deglacial unit

Hydrostratigraphic unit	Volume (m^3)	Facies proportion (%)
Glasford deglacial unit		
Coarse-grained sediment	3.06×10^9	54
Fine-grained sediment	2.63×10^9	46
Total	5.70×10^9	100
Tabular body		
Coarse-grained sediment	2.21×10^9	46.1
Fine-grained sediment	2.59×10^9	53.9
Total of unit	4.81×10^9	84.4
Champaign valley fill		
Coarse-grained sediment	8.51×10^8	95.6
Fine-grained sediment	3.88×10^7	4.4
Total of unit	8.90×10^8	15.6

Model consistency and uncertainty

Higher quality data (rank 4 and 5 boreholes, Table 2; and geophysical profiles) better constrain the surfaces of the

Table 7 Hydraulic conductivities for samples taken from the study area calculated using empirical calculations

Hydrostratigraphic unit/ hydrofacies assemblage	Average hydraulic conductivity (K_G) (m/s)
Glasford deglacial unit[a]	4.93×10^{-6}
Tabular body	
C	3.97×10^{-8}
B	4.50×10^{-5}
A	2.48×10^{-8}
Unit average	5.27×10^{-6}
Champaign valley fill	
V3	7.35×10^{-6}
V2	2.77×10^{-8}
V1	5.85×10^{-6}
Unit average	4.02×10^{-6}

[a] See electronic supplementary materials (ESM) for complete BH-1–7 K calculations and empirical equations used

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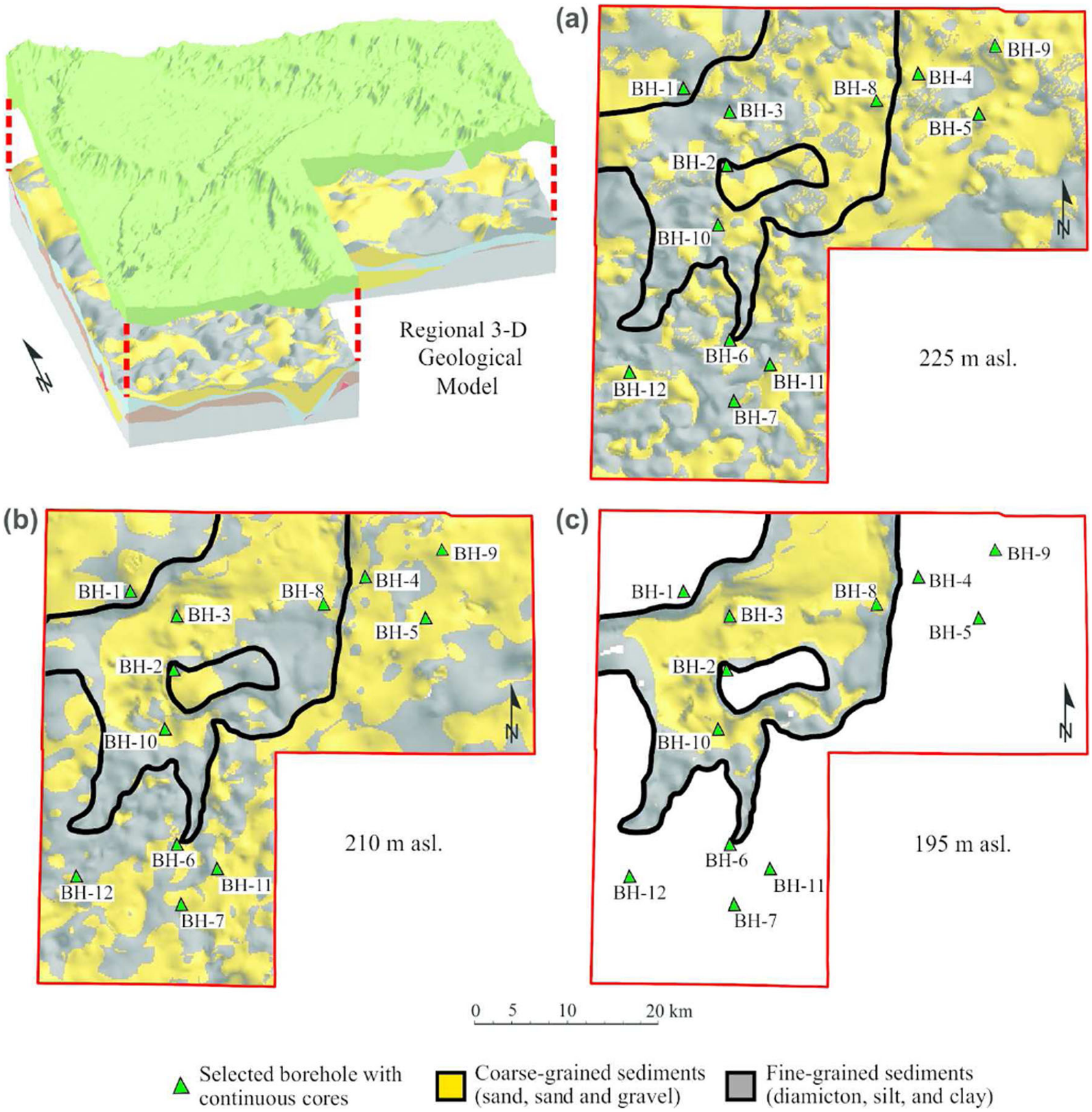

Fig. 10 A plan view of the distribution of coarse- and fine-grained sediments in the Glasford deglacial unit shown at elevations of **a** 225, **b** 210, and **c** 195 m asl. These distributions are draped on hillshaded surfaces with a vertical exaggeration of 25 times. The sediments are assigned to the composite hydrofacies assemblages (i.e., *V1*, *V2*, and *V3* and *A*, *B*, and *C*) of the Glasford deglacial unit. At 195 m asl, most sediments in the Champaign valley are interpreted to be coarse grained

Glasford deglacial unit. Uncertainty increases with distance from these data points as more boreholes with lower-quality data are used to construct the model. However, there are a number of subjective factors that also affect the uncertainty in the model (e.g., Nilsson et al. 2007). These include the degree of geological complexity, experience and expertise of the modeller, dimension of the data (i.e., 2-D, 3-D), and distribution of higher-quality data (Kaufmann and Martin 2008). Visual comparisons of modelled hydrofacies assemblages with high-quality downhole geophysical logs provided a way to verify how the model fits that data and how it is extrapolated away using geological rules. Tools available in the gOcad software allowed for quality checking of borehole geophysical data with interpretations of geologic data for multiple wells in the Glasford deglacial unit at once. Cross sections were constructed to include downhole geophysical data to compare material type represented by the gamma log with coarse- and/or fine-grained sediment in core (coarse-grained sediment is <60 CPS) as part of modelling the unit (Fig. 11, cross-section D–D′). The model therefore provides a geological interpretation of the subsurface stratigraphic architecture and hydrofacies assemblage distribution, which honour the data. The model is considered most appropriate for use in regional studies (i.e., hydrostratigraphic unit and hydrofacies assemblage scale; Fig. 6). While it may capture more local features, especially in the red zones of Fig. 7, it should not be used for other purposes than regional assessments and at larger scales without considering new high quality data.

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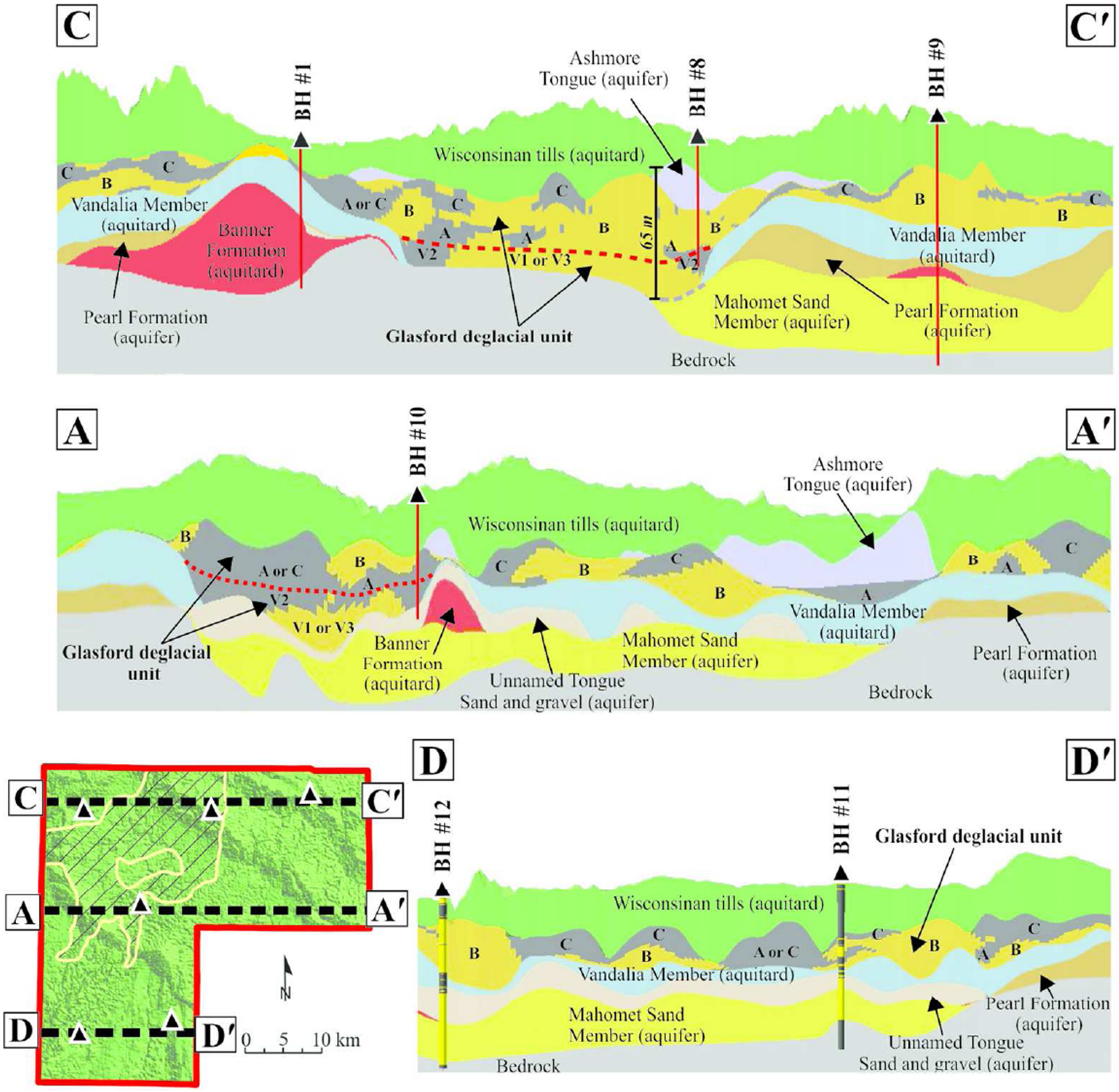

Fig. 11 Cross sections showing hydrostratigraphic units along a west to east transect in three parts of the study area (Fig. 2). For the Glasford deglacial unit and downhole geophysical logs (*BH-11* and *12*), deposits of coarse- and fine-grained sediment are delineated by the *yellow and gray shading*, respectively. The hydrofacies assemblages are also labeled. The *dashed red line* delineates the boundary between the tabular body and fill in the Champaign valley, and the *dashed gray line* (in section *C–C′*) separates coarse-grained fill in the Champaign valley from the Mahomet Sand Member. The vertical exaggeration of the cross section is 25 times. The *yellow-outlined stippled polygon* on the inset map outlines the boundary of the Champaign valley

Discussion

Determination of the hydrogeologic units of the Glasford deglacial unit

In previous hydrogeological studies of central Illinois, saturated deposits of sand and gravel interpreted as aquifers had to be at least 1.5 m thick (Kempton et al. 1982). The deposits of sand and gravel composing the Glasford deglacial unit were described as typically thin and limited in areal extent and were not delineated (Larson et al. 2003b). The unit was considered an aquitard for the most part. However, the results of this study suggest that the coarse-grained sediment is of greater distribution and thickness (Table 5), which leads us to question the aquitard interpretation for the unit. The vertical stacking of coarse- or fine-grained sediment in the Glasford deglacial unit may form local aquifer zones and discontinuous aquitards whose intricate arrangements could affect the flow of groundwater within the unit and potentially provide hydraulic connections to deeper aquifer units (Pearl Formation and Mahomet Sand Member; Fig. 3). The variable hydraulic conductivities calculated for these sediments imply that their different physical characteristics would control the overall flow of groundwater.

Important aquifer zones, possibly connecting with deeper aquifers, are likely to exist in areas where the model suggest hydrofacies assemblages V1, V3, and B overlie each other forming a combined permeable assemblage of more than 20 m (e.g., Fig. 11). The deposits of

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coarsest sand and gravel assigned to these hydrofacies assemblages are considered to be potentially the most productive aquifers in the Glasford deglacial unit (Stumpf and Dey 2012). Laterally continuous deposits of coarse-grained sediment primarily in the Champaign valley further increase the potential aquifer storage. In contrast, although deposits of fine-grained sediment (hydrofacies assemblages V2, A, and C) are delineated in the Glasford deglacial unit, they are in fact highly heterogeneous and too discontinuous to be considered aquitards with much integrity (Figs. 10 and 11). These fine-grained sediments have an average hydraulic conductivity of 3.01×10^{-8} m/s, which is consistent with aquitard materials in Illinois (Berg et al. 1984). However, it is suggested that the discontinuous nature of these sediments and their internal complexities (e.g., beds of sand and gravel interstratified with silt and clay layers) limit the ability of these sediments to be confining layers that prohibits the movement of groundwater to a significant degree.

Hydraulic connections may exist between aquifer materials in the Glasford deglacial unit and deeper aquifers such as the Mahomet aquifer. In Fig. 11, a cross section (*C*–*C*′) is shown that includes the Glasford deglacial unit and the other hydrostratigraphic units. A hydraulic connection is inferred between deposits of sand and gravel in the Ashmore Tongue, Glasford deglacial unit, and the Mahomet Sand Member, which collectively are 65 m thick. In the cross section, the depiction of many discontinuous bodies of coarse-grained sediment that, at least, locally appear to be hydraulically connected with deeper aquifer units is further complicated by the wide ranging hydraulic conductivities estimated for the Glasford deglacial unit.

Hydrostratigraphic aquifer/aquitard hybrid unit

As previously mentioned in the 'Introduction' section, the Glasford deglacial unit was initially considered an aquitard unit in regional hydrogeological investigations (Larson et al. 2003a). However, the modelling described here clearly shows that the unit contains well-defined permeable zones, especially in the Champaign valley. Hydrofacies assemblage V1, for example, is homogenous enough and appears to be laterally extensive to form at least small aquifer zones within the unit. Nonetheless, it would be misleading to refer to the Glasford deglacial unit as an aquifer due to the extensive tabular body, which contains an important proportion of aquitard-type material. These architectural elements (Champaign valley and tabular body) could form two distinct hydrostratigraphic units, but assigning the tabular unit to an aquitard would remain problematic and misleading conceptually and could lead to erroneous simplifications in future modelling of groundwater. In addition, the Glasford deglacial unit is bounded by surfaces defining regional aquitards and aquifers. It is therefore useful conceptually, but also from a modelling perspective, to map the Glasford deglacial unit as two hydrostratigraphic units with internal contrasting hydrofacies assemblages as opposed to splitting it into numerous discontinuous aquifers and aquitards. The tabular body, in particular, challenges the "classical" subdivision of the subsurface into aquifers and aquitards. Instead, it is proposed herein to refer to this highly heterogeneous unit as a "hybrid" hydrostratigraphic unit (Fig. 12) rather than heterogeneous aquifers or aquitards. Designation of this hybrid hydrostratigraphic unit is useful to conceptually describe highly heterogeneous deposits for hydrogeology purposes. For example, ice-contact and/or ice-marginal sediment deposited by meltwater in different depositional environments, as well as by other ice-marginal processes, are likely to exhibit a hybrid character in terms of their hydraulic properties and distribution. An example of an outcrop analog of such type of unit is shown in Fig. 13. Developing a robust hydrostratigraphic conceptual model prior to groundwater flow modelling experiments is an important step in the overall process that leads to understanding a groundwater system, and here it is argued that there is a missing conceptual piece in the hydrostratigraphic framework: units that do not represent as a whole an aquifer or an aquitard. Assigning a unit as hybrid in a hydrogeological model can help to account for the complexity of a unit, which can in turn lead to better simplifications in subsequent modelling experiments. The Glasford deglacial unit, for example, should not be considered an aquitard. It contains zones of aquifer materials, as well as confining beds interstratified with permeable zones, which may be too small and discontinuous to yield significant quantities of water to domestic wells. Future modelling studies in central Illinois should take into account the hybrid character of the Glasford deglacial unit, at least the tabular body.

A variety of complex ice-marginal landforms such as the Waterloo Moraine (Martin and Frind 1998) or the Oak Ridges Moraine (Sharpe et al. 1996) as well as other similarly heterogeneous deposits formed in other depositional environments may also contain laterally extensive hybrid units. Deposits forming the Waterloo Moraine are potentially end-members for the classification of highly complex depositional features both in terms of internal stratigraphic architecture and sedimentology and hydrofacies characteristics, even at local scales (Alexander et al. 2011). Conceptual hydrogeologic models commonly represent these features too simplistically as "layer-cake" stratigraphy containing homogeneous aquifer and aquitard bodies (Martin and Frind 1998). To more accurately represent these features is challenging and has rarely been attempted at regional scale, where they continue to be represented as a single homogenous unit (e.g., Bajc and Newton 2007). In many instances, the modelling of these complex deposits has yet to be completed at a scale and resolution that can be incorporated into higher resolution hydrogeological models. As an outcome, important groundwater flow pathways within these sediments may be generalized, overlooked, or misinterpreted. For example, subglacial channels cut into the regionally extensive Newmarket Till (aquitard) are in some places filled with deposits of sand and gravel that potentially are pathways for groundwater

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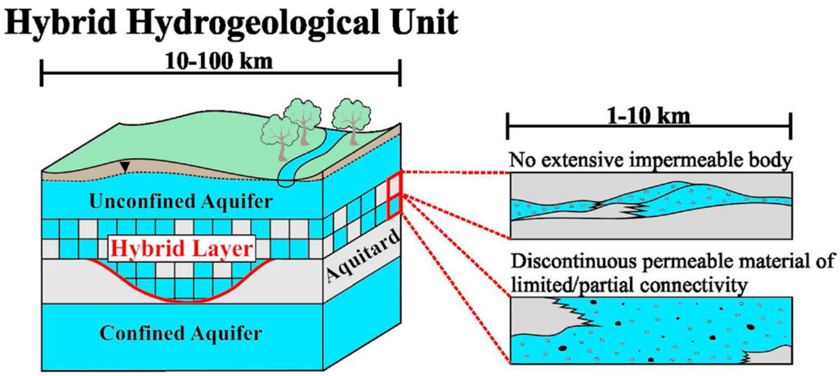
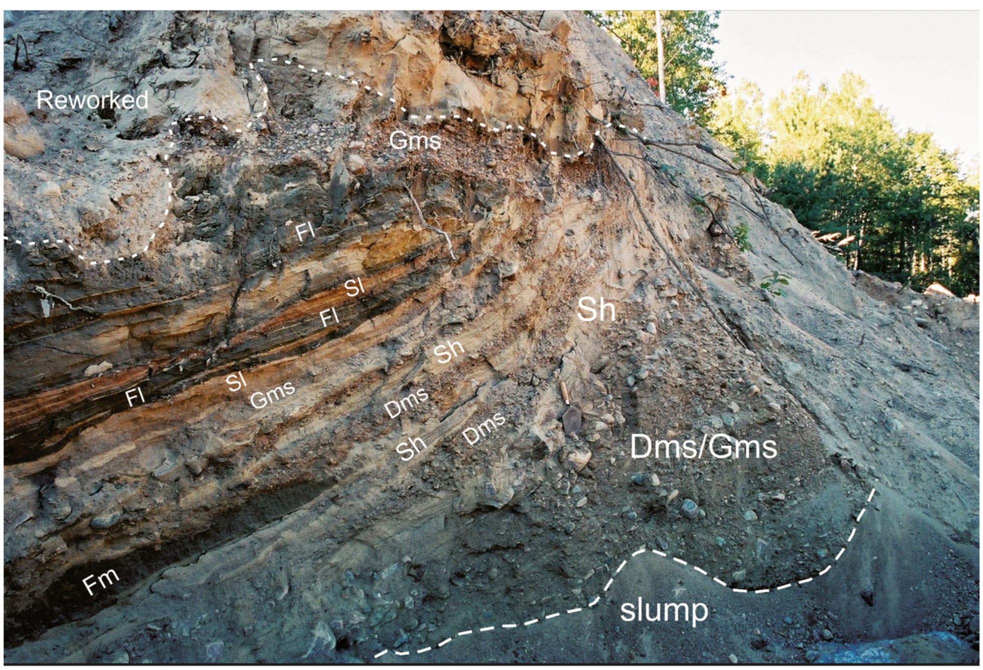


Fig. 12 Idealized conceptual model of hydrostratigraphic units. In the subsurface, aquifers, aquitards, and hybrid layers of low- to high-permeability are recognized. Hybrid layers are considered too heterogeneous (i.e., to distinguish mappable discrete hydrostratigraphic subunits) even at a regional scale to distinguish between an aquifer and aquitard. The 'hybrid layer' includes discontinuous layers of coarse- and fine-grained sediment that locally are considered aquifers or aquitards

recharge to deeper glacial aquifers, but also by finer-grained sediment that inhibit groundwater flow, and thus complicate the overall hydrostratigraphic framework (Sharpe et al. 1996, 2002). Also, the complexity of the sediment assemblages found in these channels is difficult to map. Classifying these deposits as hybrid units and providing intra-unit bounding surfaces for numerical modelling of groundwater flow (e.g., Fig. 8c) may assist



Dms- Diamicton: matrix-supported massive.

Fl- Silt & clay: fine laminations often with minor fine sand and very small ripples.

Fm- Silt & clay: massive.

Gms- Gravel: matrix-supported, massive.

Sh- Sand: very fine to coarse and horizontally/plane bedded or low angle cross-laminated.

Sl- Sand: laminated.

Fig. 13 Facies assemblages analogous to those found in the Glasford deglacial unit. The facies assemblages shown are exposed in an outcrop in Ontario, Canada, and interpreted as ice-contact/proximal sediments deposited in a subaqueous environment. Similar deposits are found along ice margins in glaciated terrain. Note the thin discontinuous nature of the beds with contrasting texture. Such sedimentary bodies form an intricate hydrostratigraphy consisting of discontinuous low-permeability (aquitard) and high-permeability (aquifer) zones. At a regional scale, this type of heterogeneous unit is best described as a hybrid hydrostratigraphic unit.

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hydrostratigraphic characterizations and improve understanding of groundwater flow in glacial sediments.

Modelling the hybrid hydrostratigraphic unit

Geological framework models containing elements that are heterogeneous at a regional scale such as for the Glasford deglacial unit, are an important step in the analysis of complex subsurface features or systems and sediment heterogeneities. The difficulty of modelling the hybrid hydrostratigraphic unit and incorporating these units into a geological framework model with certainty depends on data distribution and quality, as well as the desired objectives of the study. In this study, it was decided to first map intra-bounding surfaces and kilometer-scale hydrofacies assemblages through deterministic methods. The next step would be to model the hybrid unit using geostatistical approaches, where the geological framework model provides a foundation for developing stochastic models of internal heterogeneity at higher resolutions (e.g., Engdahl et al. 2010; Harp and Vesselinov 2010; Weissmann and Fogg 1999). It would also be interesting to use as a way to test whether the stochastic realizations can be close to the deterministic model created for the Glasford deglacial unit and, this way, assess more quantitatively uncertainty and identify potential problematic areas in the model.

Applying stochastic approaches to extend the binary coarse-to-fine classification of hydrofacies assemblages outside of the study area (Fig. 2) would also be required where the difficulty of delineating the interconnectivity between units of coarse- and fine-grained sediments becomes too complex to use qualitative modelling approaches. For modelling the Glasford deglacial unit, the lateral continuity and repetitive succession of consistent hydrofacies assemblages allowed the internal complexity of the unit to be mappable. Thus, qualitative approaches used to create a geological framework model were successful to construct intra-bounding surfaces that delineate the sediment heterogeneities in the unit.

Finally, future work should also move into numerical modelling studies focusing on understanding the behaviour of groundwater flow through the Glasford deglacial unit and how it is affected by the newly recognized hydrofacies complexity.

Conclusions

The study of the shallow subsurface geology (within 300 m of the land surface) continues to be a challenge and is generally focused where data are required for groundwater and engineering testing. This information is especially important where there is an ongoing demand for geological information from county and municipal governments, consultants, industrial users, and the public to determine the availability of groundwater resources and construction aggregate, and also to protect groundwater resources from contamination.

The case study presented herein shows the importance of characterizing complex and discontinuous hydrostratigraphic units that may be found above or in-between more homogenous and laterally extensive aquifers and aquitards. In the study area located in central Illinois, the buried regional aquifer is the Mahomet aquifer (supplying >200,000 m^3/day, and mean hydraulic conductivity of 100 m/day; Roadcap et al. 2011), which is overlain by an extensive till aquitard (Vandalia Member). This aquitard is in turn overlain by a highly heterogeneous unit, the Glasford deglacial unit, whose hydrogeological importance was recognized only recently. The deposits composing this unit were in the past interpreted as an aquitard, but this subsurface investigation has led to the identification and mapping of two major architectural elements, the Champaign valley and an overlying tabular unit, which have contrasting hydrofacies assemblages. The Champaign valley contains a permeable hydrofacies (V1) that may potentially control the transmission and storage of enough groundwater for domestic uses (aquifer zones). However, a significant volume of fine-grained sediment was modelled, comprising 46 % of the overall Glasford deglacial unit, and up to about 54 % of the tabular unit which overlies the Champaign valley. Nonetheless, textural variability of the fine-grained hydrofacies assemblages and their lateral discontinuity, suggest that they may not have a high degree of aquitard integrity. This model is further complicated by the fact that the underlying Vandalia aquitard is locally eroded and thus potentially favourable to localized hydraulic connections to the underlying Mahomet aquifer. The modelling has helped identify several potential hydraulic windows in central Illinois, which would require further detailed subsurface mapping and characterization.

The geological model developed in this study will contribute towards acquiring a better understanding of the complex subsurface geology and hydrostratigraphy of central Illinois. More specifically, it gives insights into the heterogeneous character, at the kilometer-scale, of a buried ice-marginal deposit that formed during the deglaciation that followed the penultimate (Illinoian) glaciation. Overall, the Glasford deglacial unit forms a complex hydrostratigraphic unit challenging the aquifer-aquitard concept. It is argued herein that some ice-contact or ice-marginal sediments may be laterally extensive as a whole, yet internally too heterogeneous to be mapped as aquifers or aquitards even at a regional scale. Because several other deposits in glaciated terrains, and in other settings as well, have been reported to contain such highly heterogeneous units, a new conceptual "hybrid" hydrostratigraphic unit is proposed to better describe them in conceptual hydrogeologic models. Hybrid units consist of small aquifer zones interstratified with discontinuous confining layers containing permeable lenses too small to yield enough water. This new hybrid layer is meant to augment the traditional aquifer/

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aquitard designation in order to highlight the heterogeneous character of certain deposits prior to the development of multi-layered hydrostratigraphic grids for regional groundwater modelling.

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